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CAPACITORS FOR VACUUM OPERATION WITH A
PULSED PLASMA LOAD Final Report (Fairchild
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HIGH ENERGY DENSITY CAPACITORS
FOR VACUUM OPERATION WITH A
PULSED PLASMA LOAD

FINAL REPORT
FAIRCHILD REPUBLIC COMPANY
MS172R0002

William J. Guman

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FAIRCHILD

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ABSTRACT

This report presents the details and results of the effort of designing, fabricating, and testing of a 40 joules/lb (88.2 joules/Kg) high voltage energy storage capacitor suitable for operating a pulsed plasma thruster in a vacuum environment for millions of pulses.

Using vacuum brazing and heli-arc welding techniques followed by vacuum and high pressure helium leak tests it has been possible to produce a hermetically sealed relatively light weight enclosure for the dielectric system.

An energy density of 40 joules/lb was realized with a KF-polyvinylidene fluoride dielectric system. One capacitor was D.C. life tested at 4 KV (107.8 joules/lb) for 2000 hours before it failed. Another has exceeded 2670 hours without failure at 38.3 joules/lb. Pulse life testing in a vacuum has exceeded 300,000 discharges with testing still in progress. D.C. life test data has shown a small decrease in capacitance and an increase in dissipation factor with time. Heat transfer from the load to the capacitor must also be considered besides the self-heat generated by the capacitor.

ACKNOWLEDGMENT

The author would like to acknowledge the valuable contributions and suggestions of several key individuals who participated at different phases of this effort. Mr. R. Turner of Ceramaseal provided valuable suggestions for implementing the vacuum brazed high voltage stud assembly. Mr. P. Hoffman with the assistance of Mr. R. Cooper of Maxwell Laboratories were responsible for what appeared an almost impossible task of designing and integrating the dielectric system into the hardware provided to them. Mr. W. Pavloff of Fairchild Republic's Quality Assurance Dept. performed a leading role in generating and maintaining quality assurance documentation. Since it is not possible to list by name all of the other individuals who contributed in some measure to the success of this program, the author would like to collectively thank them all.

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1.0 INTRODUCTION

1.1 BACKGROUND

Pulsed plasma thrusters require highly reliable low inductance energy storage capacitors which will operate in a hard vacuum for many years and be capable of discharging millions of pulses into a load whose dynamic impedance is roughly 10 milliohms. It is furthermore required that the energy density (joules/Kg or joules/lb) be as large as possible. When integrated to a thruster, the thruster nozzle acts as a heat source and heat transfer from the nozzle to the capacitor becomes another factor to be considered besides the self heating of the capacitor. In a very early program⁽¹⁾ radiation cooled Mylar capacitors having an energy density of 10 joules/lb (22 joules/Kg) were successfully tested without failure to 3×10^7 pulses in a vacuum. In a later program⁽²⁾ it was possible to test an improved version of a radiation cooled Mylar capacitor to 2.95×10^6 pulses without failure at an energy density of 16.4 joules/lb (36.2 joules/Kg). This latter test was performed in a vacuum with a 220 joule thruster. This latter test represents about 3,390 lb-sec of total impulse before the test was voluntarily terminated. It is presently believed that no major increases in the energy density of the Mylar dielectric system will be realized.

The present effort is concerned with the design, fabrication and testing of a space qualified high energy density capacitor utilizing a relatively new dielectric KF film polyvinylidene fluoride.* This material was utilized in two previous capacitor studies^{3, 4} and was shown suitable for the low pulsing frequencies (less than 1 Hz) to be encountered with pulsed plasma thrusters. In one of these two studies⁴ it was shown that a premature capacitor failure was due to the loss of the dielectric fluid through leaky soldered and welded joints of the capacitor container when the capacitor was operated in a vacuum. Because of this latter observation the best possible precautions were taken at each phase of the assembly of the capacitor being reported upon to assure leak tightness of the final unit in a vacuum to 1×10^{-8} cc/sec of helium. Only by this approach would it be possible to shift the failure mechanism exclusively to the dielectric system of the capacitor.

*Kureha Corp. of America, 420 Lexington Ave., New York

This report presents the details and results of the effort of designing, fabricating and testing a 40 joules/lb (88.2 joules/Kg) high reliability capacitor suitable for operating a thruster for a goal of up to ten million pulses in a vacuum environment.

1.2 DESIGN APPROACH

More than 15 years of experience with energy storage capacitors from the Bendix Corporation, Corsen, Component Specialists, C.S.I., Dearborn, Marshal Industries, and Maxwell Laboratories has revealed that capacitor manufacturers are capable of producing excellent dielectric systems. However, they generally ignore the vacuum environment in their capacitor design. Acceptable capacitor life in a vacuum environment has been previously demonstrated at Fairchild Republic only after a given capacitor manufacturer's capacitor enclosure surrounding the dielectric system is reworked after it is received from the manufacturer. The use of vacuum compatible (i.e., space approved) epoxy applied over all seams of the capacitor has proven to be a most effective means of obtaining acceptable vacuum life of most capacitors. Such a sealing technique is usually not suitable for multi-year space flight applications. MIT Lincoln Laboratory approached the problem of fabricating leak tight capacitor cans by having the high voltage bushing assembly vacuum brazed and subsequently helium leak tested. In their approach the rear lid of the capacitor was gas welded to the can and a fill hole shoulder was vacuum brazed to the lid. Only two leaky capacitors out of a very large lot were uncovered by MIT Lincoln Laboratory after more than 6 months of being fabricated. No redundant seals were used by MIT other than Fairchild's approach of using epoxy around the bushing assembly. The one leak discovered at MIT Lincoln Laboratory appeared at the vacuum brazed fill hole shoulder at the back lid. The other leak appeared to be due to a microscopic (impurity) pinhole in the material of the lid. This latter leak could have been eliminated by the use of a double vacuum melt material. To eliminate the possibility of a leak from developing across the back lid fill hole shoulder, Fairchild Republic machined the back lid out of double vacuum melt stainless steel and the machining included an integral fill hole shoulder. This approach eliminated the interface between the shoulder and the back lid.

The fill plug which is screwed into the drilled and tapped machined shoulder in the lid of the capacitor is soldered to the shoulder by the capacitor manufacturer. A redundant epoxy seal is subsequently applied over the soldered joint. Similar to MIT

Lincoln Laboratories approach, a vacuum brazed and helium leak tested high voltage capacitor stud assembly was also used in this effort. A redundant seal of an approved epoxy was subsequently applied over the vacuum brazed and helium leak tested interface.

To facilitate connecting the capacitor windings to the high voltage capacitor stud, the stud is generally provided with a concentric hole bored through it. The capacitor winding connection is fed into this hole and then soft soldered inside the stud. This solder is applied "generously" by the capacitor manufacturer in order to "seal" this opening into the capacitor. Fairchild Republic had a small cap placed over the end of the stud and had this cap soldered to the stud. This approach provided a redundant seal at this location on the capacitor.

The longest seam of the capacitor assembly is located at the perimeter of the rear lid where it contacts the capacitor can. The rear lid was machined to present a slip fit between itself and the I.D. of the capacitor can. These were subsequently heli-arc welded together. Two helium leak tests were subsequently performed on this weld. The first involved a leak test with an evacuated capacitor and a subsequent one with a pressurized capacitor. Only after each capacitor passed these two leak tests was it impregnated and sealed by the fill plug. A final high temperature and vacuum leak test were also performed. A machined redundant ring seal was subsequently epoxied over this leak tested weld.

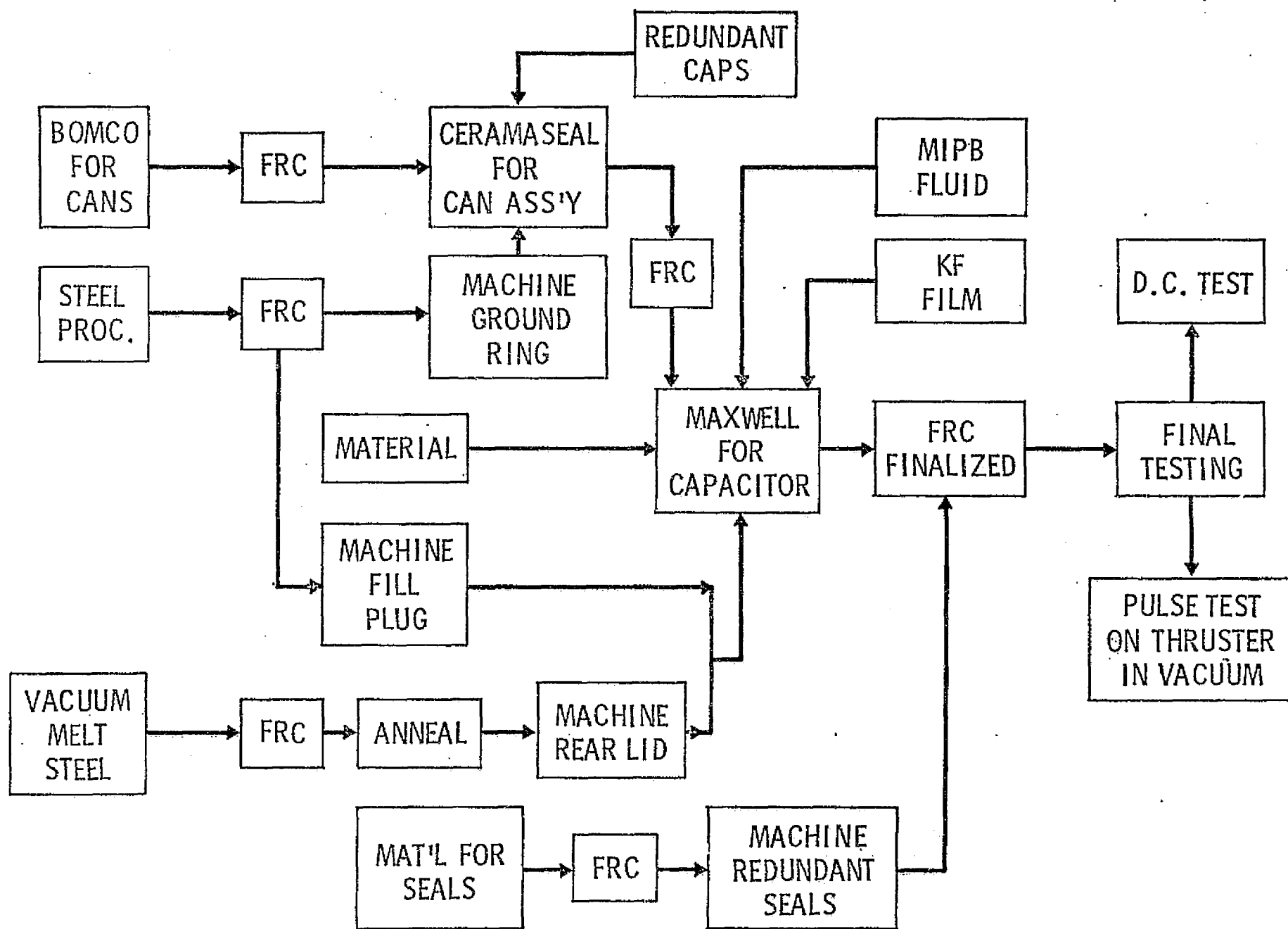
While electron beam and laser welding techniques were evaluated during this effort, the final heli-arc welded approach was selected for two reasons: 1) it can be more readily implemented by almost any manufacturer and 2) the following assessment: The feasibility of E.B. welding was discussed with Mr. DeLalio of E.B. Welding Industries in Farmingdale, N.Y. One of the requirements for E.B. welding would require the use of a low carbon steel such as 304L, 316L, 304 or even 316 for the capacitor can. Several other pertinent factors also became evident. To avoid burning the material on starting the weld it would be necessary to provide a small landing of material to start and terminate the beam. This excess material could be trimmed off after the weld is completed. Another item that became evident was that it would be extremely difficult to maintain the desired cleanliness in the production vacuum tank in which the E.B. welding would occur. The unimpregnated capacitor windings would have to be located in the capacitor can and the required evacuation for E.B. welding would also evacuate the inside of the capacitor can. On venting the

chamber to air after welding it would be possible to ingest contaminating material through the fill hole into the capacitor as the vacuum chamber is vented to air. The use of filters was considered. Because of the large number of uncertainties that could be encountered it was concluded that heli-arc welding followed by helium leak tests should be used instead of E.B. or even laser welding.

1.2.1 Manufacturing Plan: The approach taken in the present effort was to consider the capacitor an energy storage system and to utilize the know-how of several specialty vendors during the various fabrication phases of the capacitor to realize the high energy density and leak tightness required. Fairchild Republic performed the overall mechanical design and coordinated the entire effort with the various vendors. Fairchild Quality Assurance personnel performed inspections and witnessed critical tests at several of the vendor facilities. Double vacuum melt stainless steel was procured from Latrobe Steel Co. in Latrobe, Pennsylvania. The capacitor case was deep drawn by C.B. Kaupp and Sons, Inc. in Maplewood, New Jersey. The high voltage bushing assembly was fabricated and vacuum brazed to the deep drawn capacitor can by Ceramaseal, Inc., New Lebanon, New York. They also heli-arc leak tested the brazed assembly. Maxwell Laboratories in San Diego, California fabricated, installed, impregnated, leak tested and sealed the dielectric system in the hardware provided to them. Redundant sealing and final testing was subsequently performed at Fairchild Republic.

Figure 1 presents the manufacturing plan of the effort. The interrelationship of the various vendors cited above is noted. The biggest problem encountered was the fact that many of the operations could not be performed until a previous vendor completed his effort. Delays in obtaining material were encountered by several vendors. The most critical long lead item was the double vacuum melt stainless steel. This item was difficult to procure in the present program and will probably be even more difficult to obtain in future efforts in the small lot sizes required for fabricating a few capacitors.

Figure 1. Manufacturing Plan of the Effort



2.0 TECHNICAL DISCUSSION

2.1 FABRICATION DETAILS OF COMPONENTS

Several drawings and documents were generated which present specific details of of the requirements of this effort. Tables 1 and 2 present a listing of applicable drawings and applicable documents, respectively. The technical discussion to be presented below will discuss details of implementing the requirements as established by the documentation presented in Tables 1 and 2.

TABLE 1. LIST OF APPLICABLE DRAWINGS

A. Fairchild Republic Drawings:

<u>Dwg. No.</u>	<u>Title</u>
MS175D1000	Can - Capacitor Assembly
MS175D1020	Lid - Capacitor Assembly
MS175D1030	Plug - Capacitor Assembly
MS175D1040	Stud Details - Capacitor
MS175D1050	Ground Ring - Support, Capacitor Assembly
MS175D1060	Checker Assembly Capacitor
MS175D1090	Capacitor Assembly

B. Ceramaseal Drawing:

809C8968 Rev. B Can Assembly

TABLE 2. LIST OF APPLICABLE DOCUMENTS

Fairchild Republic Documents:

MS005S2300 Rev. C	Specification for High Energy Density Pulsed Discharge Capacitor for Space Flight Application
MS005S2301	Product Specification for Capacitor Can Assembly MS175D1060

2.1.1 Capacitor Can: To preclude the possibility of the presence of any porosity in the capacitor can material, the feasibility of using type 304L (or any other low carbon stainless steel) double vacuum melt stainless steel rolled into sheet form was considered. Since it was not possible to locate such material, certified 304L to specification QQ-S-766 was used instead. It was learned that rolled sheet is generally found to be free of the type of inclusions or impurities which would manifest itself as porosity in a vacuum. Since the final cases would be Helium leak tested it was concluded that the approach selected would be a low risk approach.

The results of preliminary calculations performed on the dielectric system suggested that a 7.25 in. (18.4 cm.) long deep drawn can would be required. The vendor was unable to deep draw a can to this length and maintain the tolerances called for. Prototype tests at Maxwell Laboratories showed that the capacitor can need only be 5.5 in. (14 cm.) long. No problems were encountered in deep drawing the cases to this length with the requirement that the opening at the bottom of the can be 4.075 ± 0.005 in. for a length of 0.75 in. from the open end. It was also required that the wall thickness be 0.025 in. thick over this length. Perpendicularity of the walls of the can were to be held to within 0.005 in. with respect to the closed end of the can. The tolerances at the open end were required to enable the best possible heli-arc weld to be obtained between the rear lid and capacitor can by being able to control the slip fit tolerances between the can and the lid. Besides the above dimensional requirements it was required that dies and flat blanks be cleaned before each drawing to preclude foreign matter from becoming imbedded into either the inside or outside walls of the container. A final stress relief was also required.

After the capacitor cases were received, Fairchild Republic machined a 0.915 ± 0.002 inch diameter hole in the center of the closed end of the can for the high voltage stud assembly. This hole was machined concentric within the closed end within a TIR of 0.005 in.

Of 20 capacitor cases fabricated, two units were oversize by 0.001 inches and one was slightly out of round. Both of these units were accepted as practice units for assessing later operations.

2.1.2 Flexible Back Lid. It is well known that the dielectric system expands and contracts with temperature changes. Fairchild Republic's approach was to design the rear lid to behave as a flexible diaphragm in order to flex with temperature changes. This requirement is particularly important since the dielectric system is sealed in the capacitor at $-15^{\circ}\text{C} \pm 2^{\circ}\text{C}$. For all temperatures above this temperature, one has the dielectric fluid completely in contact with the walls of the capacitor. Material voids are therefore precluded from occurring either under normal temperatures or zero g environmental conditions.

All of the requirements sought of the back lid could be realized if it was machined out of a double vacuum melt stainless steel. The peripheral edge of the lid is machined to the thickness of the can where it is welded to the can. The boss containing the fill plug hole is also machined into the lid thereby eliminating one seam. The diaphragm action was achieved despite work hardening by alternately machining the two sides of the "diaphragm" until the required 0.018 in. thickness was achieved. Final desired bowing of the lid occurred with the exterior surface being concave. This final geometry prevented "oil canning" and also assured that the flexible lid could only flex outward after the capacitor is impregnated at -15°C .

The O.D. of each lid was machined to be a slip fit i.e. 0.001 to 0.002 in. less than the measured I.D. of the capacitor can to which it will be mated. The lid and capacitor can were subsequently serialized to maintain "mated" pieces.

The lid was machined of type 316 thermal induction plus vacuum arc remelt stainless steel. The material was procured from Latrobe Steel Co., Pennsylvania. The chemistry met specification RDT-E-13-8T except for arsenic and the material was certified to meet Latrobe Z0-63 ultrasonic specifications. Prior to machining, Fairchild Republic had the material annealed by heating it to 1900° Fahrenheit for one hour and then water quenching it. Approximately one hour per inch of thickness was allowed to reach temperature.

2.1.3 Ground Ring. The ground ring serves as an electrical interface between the capacitor and the external thruster load and it is located at the high voltage stud end of the capacitor. The electrical interface of the ground ring must be parallel to the mounting surface located on the high voltage stud and be displaced from it by 0.042 to 0.047 inches (0.107 to 0.119 cm). This latter spacing equals the thickness of the

copper stripline of the thruster (which becomes screwed down to the ground ring) and also that of the Mylar insulation to be positioned between the positive and negative striplines. The threaded mounting holes in the ground ring are made as blind holes so that mounting screws cannot extend through the ground ring and inadvertently penetrate the capacitor can.

In an earlier effort the ground ring was spot welded to the capacitor can in order to locate it for vacuum brazing. This approach resulted in many capacitor cans leaking at the spot welds. To prevent such leakage, the ground ring in the present effort was fabricated as part of a cap which slipped over the closed end of the capacitor can. The I.D. of the protruded cylindrical part of the ground ring (see Figure 2) was machined to within ± 0.0005 inches. This very tight tolerance was requested by Ceramaseal Inc. They used this surface in the vacuum brazing tooling to align the high voltage stud assembly to achieve the required dimensional relationship, perpendicularity and concentricity requirements between the high voltage stud and the ground ring. To reduce the weight of the ground ring, thirty holes were drilled in the cap of the ground ring. These holes not only reduced the weight of the piece, but also allowed an inspection to be made of the vacuum brazed assembly. Figure 3 shows details of the cap-ground ring after it has been vacuum brazed to the capacitor can.

To assure that the electrical interface of the ground ring is parallel to the interface on the high voltage stud, the height of the ground ring was made 0.032 in. larger than the final height required. This excess material was removed and the electrical interface was machined parallel to the interface on the high voltage stud after vacuum brazing was completed. This final trimming assured that no bending moments could be imparted to the high voltage stud after the capacitor is electrically interfaced to the thruster load.

The ground ring design implemented was highly successful and in no way introduces seams or possible sources of leakage in the capacitor or bending moments on the high voltage stud. In future efforts it might even be desirable to machine an additional flange onto this ground ring assembly so that heat can more readily be transferred from the capacitor to an appropriate heat sink.

2.1.4 High Voltage Stud Assembly. Capacitor manufacturers usually procure large quantities of ceramic insulators, provide their own high voltage terminals to these and subsequently install them into their capacitor cans. These high voltage stud assemblies

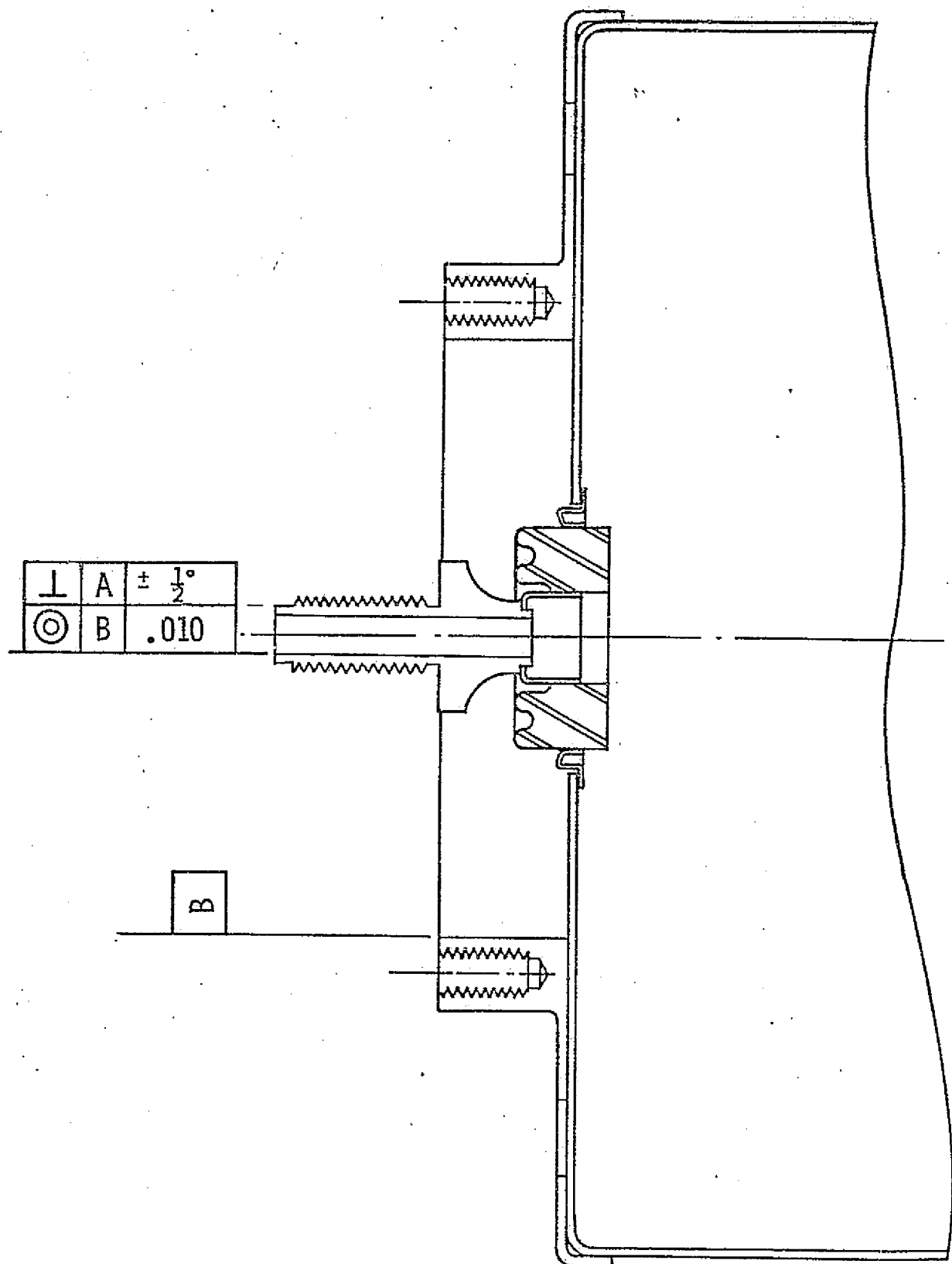


Figure 2. Details of High Voltage Stud-Ground Ring Subassembly

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Figure 3. Details of the Cap-Ground Ring
Subassembly after Vacuum Brazing

are usually solder joined to the capacitor can. Fairchild Republic's experience has shown that these solder joined assemblies tend to leak dielectric fluid after prolonged use in a vacuum environment. Potting the base of the stud assembly with a space approved epoxy generally eliminates the loss of dielectric fluid and allows reliable vacuum operation to be realized. A superior technique is to vacuum braze the high voltage stud assembly to the capacitor can and subsequently Helium leak test the brazed joint. This assembly is then redundantly sealed by epoxy potting.

Ceramaseal Inc. of New Lebanon Center, New York fabricated the high voltage stud assembly to Fairchild Republic specifications. They also vacuum brazed it to the deep drawn capacitor cans furnished to them and subsequently Helium leak tested the brazed assembly. Details of the entire assembly can be seen in Figure 3. The assembly is comprised of an Alumina insulator, a nickel-iron cap and flange and an Invar high voltage stud. Perpendicularity of the stud was required to be within $\pm 1/2^\circ$ with respect to the plane of the ground ring, and concentric to within 0.010 inches. The electrical interface on the stud shoulder was to be in the same plane of the electrical interface on the ground ring within ± 0.030 inches. (Later machining of the ground ring as discussed in section 2.1.3, provided the exact final tolerances required). To realize all of these requirements, Ceramaseal fabricated a fixture which utilized the I.D. of the cylindrical ground ring for maintaining proper alignment of all components during vacuum brazing.

Helium leak testing was carried out on each brazed assembly to 1×10^{-9} cc/sec of Helium per MIL Std 271 para. 6 using a hood method. A Fairchild Republic Quality Assurance representative witnessed these leak tests at Ceramaseal. Of 20 units fabricated, only 3 were rejected because they did not pass the leak test. This yield of 17 out of 20 units is better than the yield of 15 out of 25 basic units which was realized in another effort in which the ground ring was locally spot welded in order to align the parts for vacuum brazing.

Figure 3 shows that the top of the ceramic insulator is located below the electrical interface on the ground ring so that a redundant epoxy seal can be applied over the ceramic insulator assembly and the Helium leak tested brazed joint between it and the capacitor can. Figure 4 shows the redundant epoxy seal that is applied before the capacitor is considered test ready.

It should be noted that the stud assembly is designed to be threaded and to have a shoulder at the bottom of the threads. This technique prevents the stud from being pulled out (i.e. like a wheel puller) of the capacitor can as one tightens the electrical interface to the stud. This integral shoulder replaces a nut screwed onto the stud in earlier designs. The stud assembly is final checked to withstand 31 in-lb of torque.

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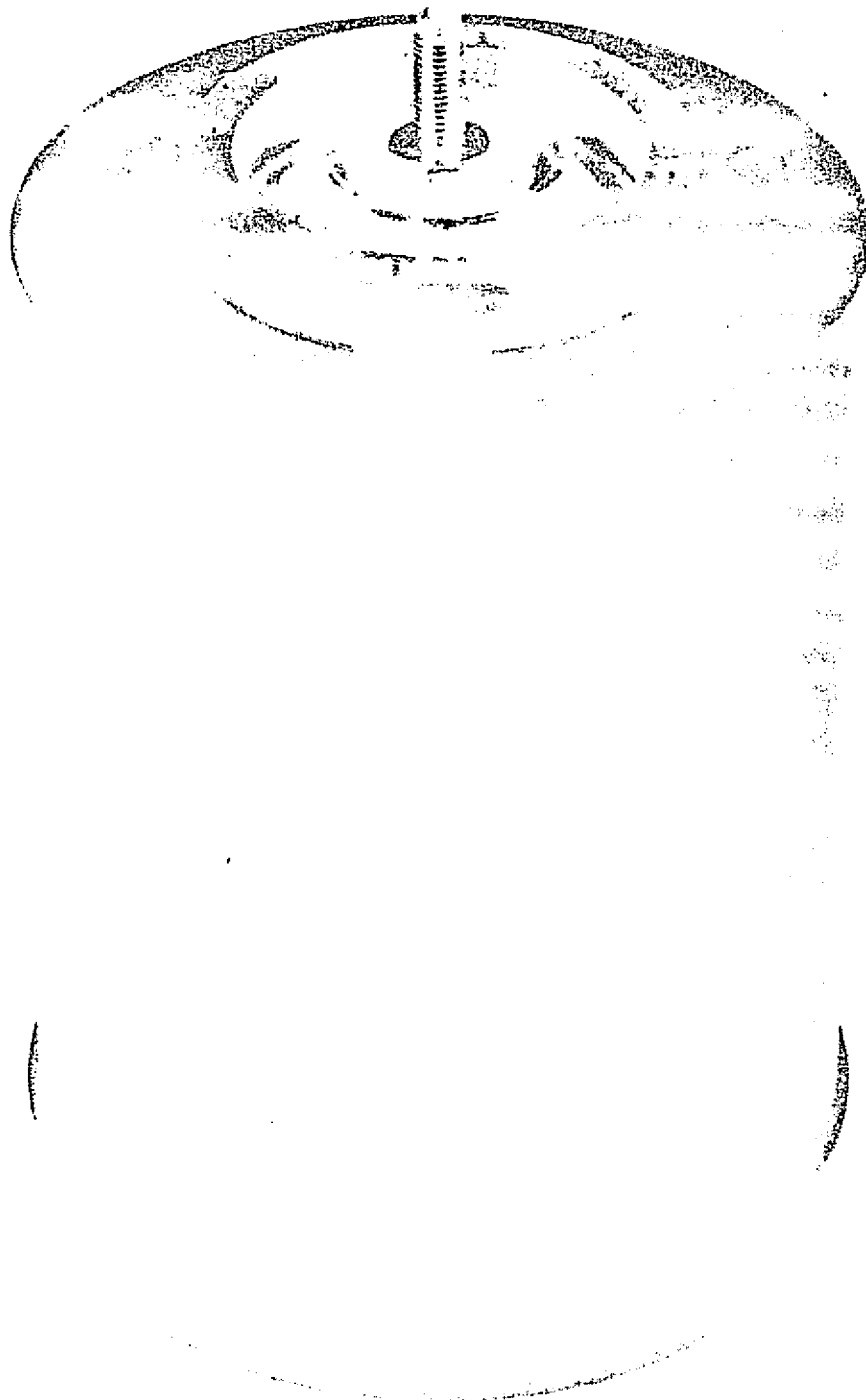


Figure 4. Redundant Epoxy Seal Applied Over the
Helium Leak Tested High Voltage Stud Assembly

2.2 INTEGRATION OF CAPACITOR COMPONENTS

2.2.1 Pre-Fabrication Effort at the Capacitor Manufacturers Facilities. Final integration of the capacitor took place at Maxwell Laboratories in San Diego, California in accordance with Fairchild Republic specification MS005S2300. Before Maxwell could integrate the components of the system, they had to design the basic K-film dielectric system as well as the extended foil hardware to interface the dielectric system to the high voltage stud assembly. Maxwells prior experience with space qualified capacitors built to Fairchild Republic's specifications on a previous flight hardware program proved to be most useful in mating the hardware as well as the quality assurance requirements of this effort.

The first effort performed at Maxwell Laboratories was to empirically establish the required design data for the final capacitors. They fabricated 20 test windings comprised of 2 layers of K-film, 1 layer of paper and the aluminum foil. The capacitance of these test samples was about 2.6 μ fd before impregnation and 4.62 μ fd after impregnation. These test pads were subsequently hi-pot tested to failure. The mean value at which failure occurred was about 7.7 KV with 15 foil edge failures and 5 bulk failures. This preliminary effort established that the requested $\pm 5\%$ tolerance in capacitance could possibly be met and also established the $\text{in}^2/\text{mil}/\mu\text{F}$ empirical constant of the system. Following this effort, two prototype 60 μ fd capacitors were built and life tested. They were charged to 3000 volts (the final use voltage will be 2335 volts) into a load whose resistance is about 0.8 ohms used an inductance of 175 μH . The pulse rate selected was 25 ppm and forced convection cooling was used to keep the capacitor case between 45°C and 50°C. One of these prototype units failed at 230,000 pulses as a bulk dielectric puncture in the center of the dielectric width, about 30% out from the core of the capacitor. The second unit failed at 976,000 pulses. Most of the time the capacitor case was around 50°C. However, due to the fact that the cooling fan was accidentally left off, operation at 70°C occurred for about an hour. An extrapolation of this higher 3 KV data to the test voltage of 2.335 KV cannot be made at this time due to the lack of test data under more widely ranging voltage conditions.

2.2.2 Fabrication Details. Details of the dielectric system is shown schematically in Figure 5. This dielectric system is wound as an extended foil system on a nylon tube with a polypropylene core and several windings of the dielectric are wound on this core before the aluminum foil is inserted. After winding to the required length,

the aluminum foil is cut off and 1 to 2 extra turns of K-film are wrapped over the aluminum. Eight current collection tabs are soldered across the high voltage end of this system. A Teflon sheet is placed over these tabs before they are bent over and soldered to the high voltage stud assembly. This stud, on final assembly, slides up into the tubular part of the high voltage stud (see Figure 2) which was vacuum brazed by Ceramaseal to the capacitor can. Eight current collecting tabs are soldered to the inside of the capacitor can at the open end (see Figure 6). These tabs will become the current ground return to the dielectric system. The dielectric system is then fully insulated from the capacitor can by wrapping polypropylene around the dielectric system and placing a polypropylene cap over the front high voltage end. This end cap extends slightly rearward over the sides of the dielectric system. After the dielectric system is inserted into the capacitor can, the eight end tabs on the can are bent over and soldered to the back end of the dielectric system. Disks of Kapton and polypropylene are placed over these and the diaphragm type back lid of the capacitor is inserted. This lid is Heli-arc welded in one continuous run to the capacitor can using a large metallic heat sink placed around the can in the vicinity of the weld. The high voltage stud assembly is then soldered in place as well as a redundant sealing cap over the unthreaded end of the stud (see Figure 4). The O.D. of this cap is less than the root diameter of the thread. A die is then run over this section to remove any traces of solder in the threads of the stud. At this point, the dry capacitance and dissipation factor are measured and recorded (see Table 3). The system is then dried overnight at an elevated temperature before the inside of the capacitor can was evacuated for a helium leak test of the welded lid and soldered joint at the high voltage stud. A Veeco model MS-90 leak detector was used for this purpose. Each capacitor was required to pass the Helium leak test with a leakage not in excess of 10^{-8} cc/sec. No leaks were found around any of the welds at the rear lid. However 3 units SN 11, 17 and 20 leaked around the soldered center stud. All welds were leak tight. These 3 units were repaired and subsequently they passed this leak test. After these low pressure leak tests, the units were taken to Intelcom Rad Tech in San Diego for an additional leak test with the inside of the capacitor pressurized with Helium to 15 psig. A Veeco Model MS-9 was used as the leak detector and all seams were checked under these pressurized conditions. Two units which previously passed the evacuated leak test leaked at 5×10^{-8} and 8×10^{-8} cc/sec, respectively. It is perhaps interesting to note that these two were two of the original three low pressure leaks which had been repaired.

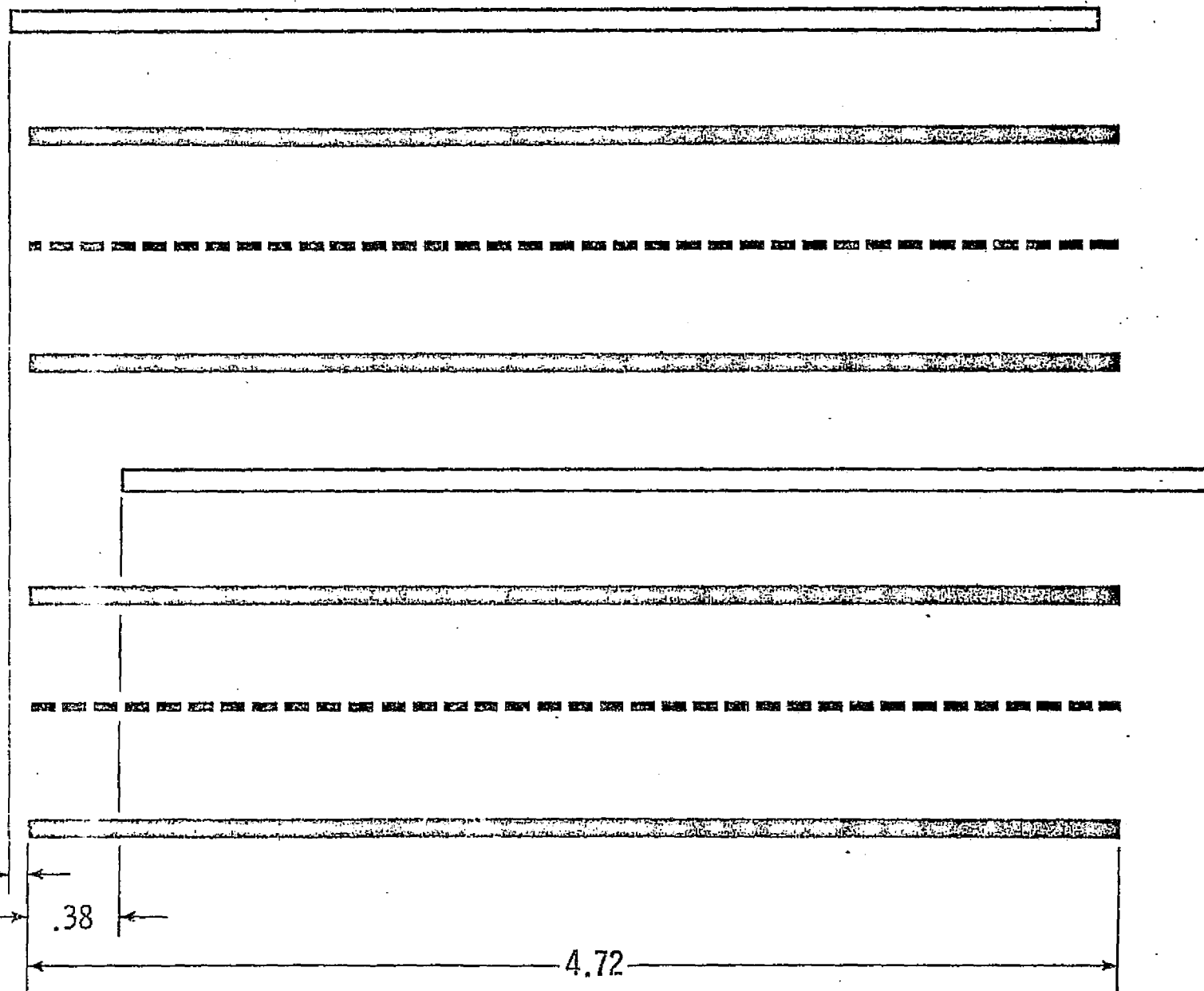





Figure 5. Dielectric System

FOIL		(0.00017)
KF FILM		(0.000354)
PAPER		(0.00025)

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Figure 6. Current Collecting Tabs at the Open End of the Can

TABLE 3. CAPACITANCE HISTORY

Serial Number	Capacitance Before Impregnation (μ fd)	Dissipation Factor Before Impregnation	Capacitance After Impregnation (μ fd)	Dissipation Factor After Impregnation
2	38.0	0.016	68.9	0.0082
3	37.5	0.016	69.4	0.0082
4	-	-	68.5	0.0081
5	38.4	0.016	69.9	0.0079
6	38.0	0.016	68.9	0.0075
8	38.0	0.016	68.9	0.0084
11	38.5	0.016	69.2	0.0080
12	38.5	0.016	68.8	0.0080
17	-	-	68.7	0.0075
18	-	-	68.8	0.0083
10	38.0	0.016	-	-
13	38.5	0.009	-	-
1	38.0	0.016	-	-

After all capacitors passed these leak tests, they were impregnated with castor oil and sealed off at the fill plug hole at $-15^{\circ}\text{C} \pm 2^{\circ}\text{C}$. This temperature was selected to prevent possible freezing (-20°C) or slush formation of the castor oil. The diaphragm like rear lid is flexed inward toward the dielectric system when the capacitor is sealed at -15°C . This approach assures that no cavities or voids can be present inside the capacitor at any temperature above -15°C .

The final acceptance tests performed at Maxwell Laboratories were carried out in accordance with the requirements of paragraph 3.6.2 of Fairchild Republic specification MS005S2300. The hi-pot voltage selected was 3.5 KVDC for 60 sec. After this was discharged, each capacitor was subsequently hi-potted to 2.5 KV for 5 sec and discharged. This latter charge-discharge cycle was repeated ten times for each capacitor at a pulse rate not to exceed 6 ppm.

All 13 capacitors passed this final acceptance test with the exception of the following favorable outcome. The capacitance requirements sought were $60 \mu\text{fd} \pm 10\%$, -5% . The final results showed that we actually realized $68.9 \mu\text{fd} \pm 1\%$. Such a tight tolerance for large energy storage capacitor is believed to be quite an achievement. This higher capacitance was considered acceptable by Fairchild Republic since the 750 joule thruster load could now be operated at 2.34 KV instead of 2.5 KV. Data generated at M.I.T. Lincoln Laboratory⁵ indicates that the life of film capacitors impregnated with castor oil varies with voltage roughly inversely to the thirteenth or fourteenth power. If the thirteenth power variation is valid, reducing the operating voltage from 2.5 KV to 2.34 KV should increase the capacitor life by a factor of 2.36 over the expected life at 2.5 KV. Another advantage to be realized is a somewhat higher power conditioning efficiency that is realized by charging the capacitors to the lower voltage.

Since the effort at Maxwell called for a final delivery of ten capacitors, three units (SN 9, 16, 20) were not accepted by Fairchild Republic. SN 9 and 16 had a splice in the dielectric system and SN 20 had a slight discoloration on the metal container.* It is important to note that these three units passed all acceptance tests and otherwise they cannot be distinguished from the ten units that were accepted.

Table 4 presents a summary of the capacitance, weight, energy density and dissipation factor realized. At the originally rated 2.5 KV the energy density achieved was 42.6 joules which exceeds program objectives.

*It is believed that this discoloration existed on the container prior to their being shipped to Maxwell Laboratories from Fairchild Republic.

TABLE 4. SUMMARY OF DATA REALIZED

<u>SN</u>	<u>Capac. (μfd)</u>	<u>E(j at 2.5KV)</u>	<u>W(gr)</u>	<u>W(lb)</u>	<u>J/lb</u>	<u>D.F.</u>
2	68.7	214.69	2287.5	5.05	42.51	0.0113
3	68.9	215.31	2312.1	5.10	42.22	0.0090
4	68.2	213.12	2284	5.04	42.28	0.0106
5	69.5	217.19	2277.4	5.03	42.18	0.0111
6	68.7	214.69	2270.5	5.01	42.85	0.0119
8	68.9	215.31	2300.3	5.08	42.38	0.0091
11	68.7	214.69	2294.2	5.06	42.63	0.0098
12	68.4	213.75	2268.1	5.01	42.66	0.0108
17	68.7	214.69	2292.3	5.06	42.43	0.0105
18	68.9	215.31	2293.0	5.06	42.55	0.0091
(9)	70.1	219.06	2300.2	5.08	43.12	0.0104
(16)	69.0	215.62	2288.1	5.05	42.69	0.0104
(20)	<u>69.0</u>	<u>215.62</u>	<u>2277.5</u>	<u>5.03</u>	<u>42.87</u>	<u>0.0098</u>
Average	68.9	215.31	2288.1	5.05	42.64	0.0103

2.3 FINAL TESTING

2.3.1 Redundant Sealing: The capacitors delivered by Maxwell Laboratories were put into the test ready condition at Republic. The final operations performed at Fairchild Republic provided the redundant sealing of all Helium leak tested joints and application of a black space qualified paint. Redundant sealing was carried out at the three seams of the capacitor. An aluminum ring was fabricated and epoxied over the Helium leak tested seam at the base of the capacitor (see Fig. 7). Teflon fixtures were made which facilitated molding the epoxy seals over the Helium leak tested high voltage stud and around the fill plug of the capacitor (see Fig. 4). After these redundant seals were applied and cured, the capacitors were painted black with Hughson Z-306 Black Polyurethane coating. A final weight measurement was made of the test ready capacitors. Table 5 compares the weights of the Helium leak tested capacitors as received from Maxwell Laboratories and the weight of the capacitor with the redundant sealing and black paint. The redundant seals and paint increases the capacitor weight by about 1.9%. At the rated 2500 volts, the energy density is still, on the average, 41.8 joules/lb.

Capacitors SN 2 and 6 will be D. C. life tested at Republic. Capacitors SN 3, 8, 11, 18 have been selected to be incorporated in the Air Force Milli-pound propulsion system for pulse life testing in a vacuum.

TABLE 5. WEIGHT COMPARISON

<u>SN</u>	<u>Weight as Received (gr)</u>	<u>Test Ready Weight (gr)</u>
2	2287.5	2331.3
3	2312.1	2355.5
4	2284.0	2327.0
5	2277.4	2721.3
6	2270.5	2314.3
8	2300.3	2344.5
11	2294.2	2337.0
12	2268.1	2310.3
17	2292.3	2335.0
18	2293.0	2336.5
Average	2287.9	2331.3

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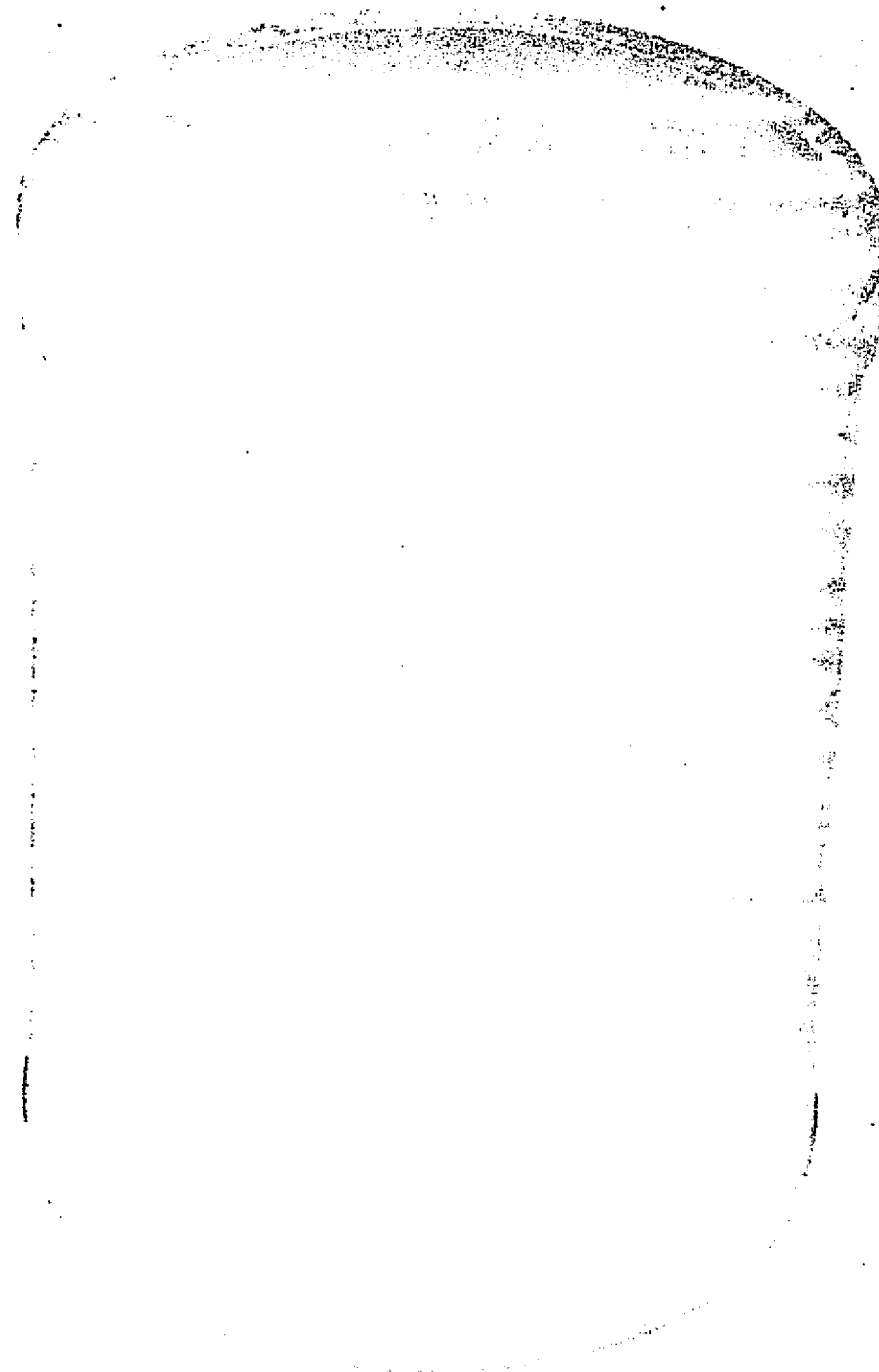


Figure 7. Redundant Seal at the Welded Base

2.3.2 D.C. Testing: Two capacitors, SN 2 and 6 were D.C. life tested. One of these (SN 2) was tested at 4 KV, whereas capacitor SN 6 was tested at 2.38 KV. The test circuit designed is a voltage divider network which allows both capacitors to be operated at different voltages from the same power supply. Additionally, two microammeters were incorporated to facilitate monitoring leakage current flow measurements during the life test. To protect these microammeters during the initial charge cycle and in the event of a shorted capacitor failure, they are switched into the test circuit whenever a leakage current reading is sought. Each of the two capacitors has its own dump resistor. Because of the very large resistive values used in the divider network, any direct voltage measurement across a leg of the divider would electrically load the circuit and an incorrect voltage would occur if not corrected. To eliminate this possible source of error, another voltage tap is made into the resistive network and the voltage drop across the lower resistance value is used for monitoring purposes. Since the resistance of the measuring equipment is significantly higher than the value of the divider of the test circuit, no corrections need be made for the current flow through the monitoring measuring probe. The calibration of the resistive divider network was performed with a Fluke Model 8300A digital multimeter. The calibration constants are 9.991V for the 4 KV capacitor and 5.9597V for the 2.38 KV capacitor with V the monitoring voltage. This latter voltage value was selected to correspond as close as possible to the 2334 volts to be used with the K-film capacitors while life testing them on a pulsed basis in the Air Force milli-pound thruster. Figure 8 presents a diagram of the test circuit. In order to monitor other basic parameters of the capacitor during the test, the capacitors are removed once a week from the test circuit and the capacitance and dissipation factor (D.F.) are measured on an ESI Model 250-DA impedance bridge. Table 6 presents the data obtained to date. It was noted that the capacitance of the 4 KV capacitor (SN 2) dropped during the first 95 hours of testing. It was decided, at this point also, to monitor the capacitance and dissipation factor on a placebo (i.e., a capacitor not being tested). Capacitor SN 12 was used as the placebo. Capacitance changes have been noted on all three capacitors. Since line voltage variations were noted, a voltage regulator was also introduced into the test circuit.

The capacitor being tested at 4 KV failed over a weekend. The elapsed time clock in the circuit did not stop at the time of failure and it is known that the failure occurred somewhere between 1970 hours and 2002 hours. This failure is not an

unexpected failure, but represents a useful data point. It should be noted that this 68.7 μ fd capacitor stored 549.6 joules during this roughly 2000 hour period, or, the energy density was 107.8 joules/lb during this time. This data point is most encouraging since this number of D.C. hours at the elevated voltage exceeds the total accumulated D.C. hours expected under pulsed conditions even for a 37,000 lb-sec total impulse pulsed plasma propulsion system.

The failed capacitor was sent back to Maxwell Laboratories for failure analysis. It was concluded that the failure was an edge margin failure localized at a foil edge at the bottom (i.e. lid end of the capacitor) of the winding about one-third the distance radially inward from the outer periphery. This failure punctured the dielectric and one of the eight current collecting tabs was thereby separated from the foil windings.

Because of the vacant space available on the test set, the failed K-film capacitor was replaced by a 65 μ fd Mylar capacitor (also from Maxwell). This capacitor is also being tested at the 4 KV level to determine if the observed capacitance and dissipation factor changes (see Table 6) with the K-film unit also occur with a Mylar capacitor. Test data (data in parentheses in Table 6) to date has shown the Mylar capacitor to be essentially stable compared with the K-film capacitor when compared over the same testing time.

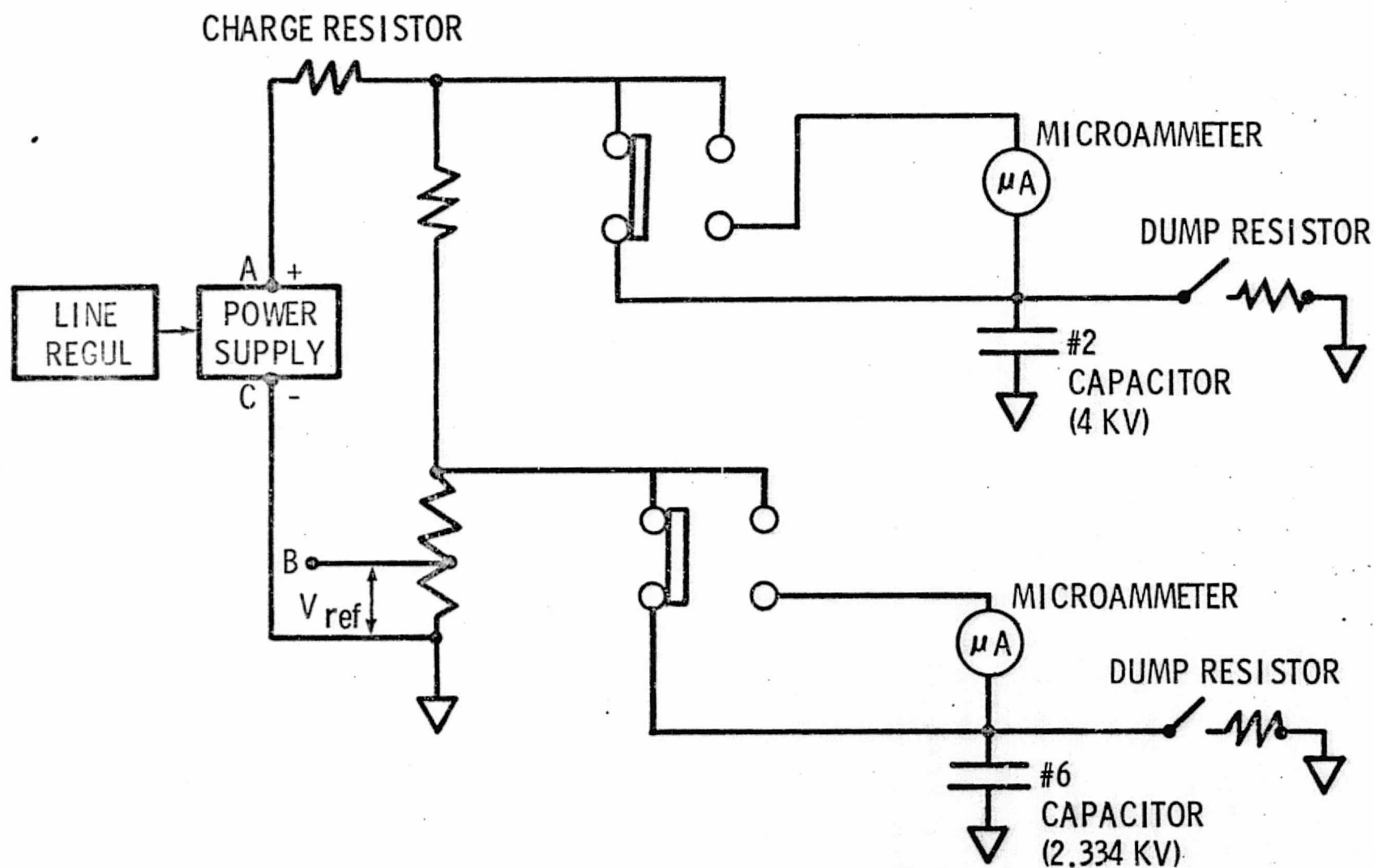
It would therefore appear that the roughly 5% decrease in capacitance and 14% increase in dissipation factor observed is a real effect. This observation is further substantiated by the fact that the placebo has not undergone any significant change over the total testing time.

2.3.3 Pulse Testing: Other than the eleven pulses performed by Maxwell Laboratories during final acceptance testing, no additional quality assurance screening pulses were performed with any of the capacitors. Capacitor SN 3, 8, 11 and 18 were installed into the Air Force life test propulsion system in order to pulse life test them in a vacuum chamber under actual load conditions. An exploratory propulsive performance test was carried out on a thrust balance to establish if the propulsive performance utilizing these K-film capacitors would be the same as that obtained with Mylar capacitors. The comparison performed with an identical nozzle load tested under the same conditions provided the following impulse bit data:

TABLE 6. SUMMARY OF CAPACITANCE AND D.F. DATA
DURING D. C. TESTING

Test Duration Hrs.	4KV		2.4KV		Placebo	
	C	DF	C	DF	C	DF
	2	2	6	6	12	12
(Maxwell Data)	68.7	0.0113	68.7	0.0119	68.4	0.0108
0	68.11	0.010	68.11	0.010	-	-
95.5	64.92	0.0133	68.23	0.0138	-	-
213.0	64.655	0.0132	67.55	0.0132	67.52	0.010
332.9	64.651	0.0121	67.23	0.0132	67.35	0.0090
500.0	64.60	0.0132	66.7	0.0102	67.60	0.0090
667.4	64.55	0.0130	66.6	0.0140	67.80	0.011
857.4	64.55	0.0135	66.31	0.0132	67.43	0.009
999.4	64.51	0.0145	65.65	0.0155	67.50	0.010
1166.6	64.63	0.0133	65.97	0.0138	67.48	0.0103
1234.6	64.75	0.0142	65.90	0.0143	67.47	0.0103
1502.2	64.92	0.0135	65.87	0.0143	67.49	0.0103
1668.7	64.83	0.0142	65.75	0.0132	67.47	0.0107
1834.9	64.83	0.0142	65.66	0.0134	67.48	0.0107
2002.9	- Failed - (replaced by Mylar capacitor)	-	-	-	-	-
2002.9	(63.07)	(0.0063)	65.73	0.0118	67.47	0.0192
2098.2	(63.54)	(0.0063)	65.98	0.0123	67.48	0.0108
2193.1	(64.43)	(0.0062)	65.97	0.0138	67.46	0.0112
2361.8	(64.75)	(0.0063)	65.71	0.0148	67.46	0.0113
2479.7	(63.97)	(0.0067)	65.80	0.0132	67.45	0.0118
2675.2	(64.81)	(0.0060)	65.56	0.0138	67.41	0.0110

Figure 8. Test Circuit Schematic for D.C. Life Testing



K-film capacitor test:	5.974 milli-lb-sec (26.67 milli-N-sec)
Mylar film capacitor test:	5.964 milli-lb-sec (26.62 milli-N-sec)

The results of this test established that no change in impulse bit amplitude could be detected when either type of capacitor was used. This result was somewhat surprising because of the higher dissipation factor (measured at 1 KHz) of the K-film capacitor.*

Pulse life testing in a vacuum was initiated with four of the capacitors connected in parallel and cooled by radiation only. Repetitive pulse testing at a 750 joule discharge level was voluntarily terminated when the capacitor case temperature reached roughly 50°C with the temperature still rising. By adding several thermocouples it was determined that heat was being transferred from the electrode nozzle to the capacitor via the current carrying copper strip lines. Several tests were carried out under radiation cooled conditions. These tests revealed that the radiator and the essentially radiatively cooled base plate on the thrust balance were unable to dissipate the heat transferred to them. It was concluded that it would not be possible to pulse life test the capacitor at a pulse rate of 0.146 Hz under thermal radiation cooled conditions. The thermal design of the propulsion system was redesigned. Each capacitor was provided a copper strap wrapped around the capacitor and terminated into a temperature controlled heat sink. In addition, the cross sectional area of the heat sinks located between the anode and cathode thruster nozzles (load) and capacitor bank were increased. These changes were effective in that it was immediately possible to pulse life test the capacitor in this conduction cooled configuration at the desired pulse rate. With a sink temperature of about 20°C (a common spacecraft sink temperature) the capacitor equilibrium temperature is about 40°C, or, about 10°C below the maximum allowable temperature of 50°C.

One capacitor (SN 8) failed during the radiation cooled tests. This failure could possibly have been due to the higher internal capacitor temperature, or due to a failure which might have been found if a quality assurance pulse screening test had been performed. This failed unit was sent to Maxwell Laboratories. This failure

* The dissipation factor above 150 KHz, roughly the pulse load discharge frequency, is not known.

was also of the edge margin type. However, the failure was unlike any encountered with the pre-fabrication sample units (see section 2.2.1). Damage to the dielectric extended completely along the longitudinal dimension of the capacitor winding. It was also observed that the castor oil was carbonized. Maxwell Laboratories concluded that this failure was not a sudden failure but that the capacitor had been short circuited for many pulses. These observations have never been seen before and are therefore difficult to explain.

The failed capacitor was replaced by another unit (SN 5) and pulse life testing was subsequently initiated with the conductively cooled system.

Figure 9 presents the capacitor temperature history for the earlier radiatively and final conductively cooled system, respectively. Over 300,000 pulses (570 hours of operation) have been produced and pulse testing in a vacuum will be continued beyond the completion date of this final report.

- ◇ A - RADIATION COOLED (VARIABLE PULSE RATE)
- B - RADIATION COOLED - PERIOD 6.7 SEC
- C - RADIATION COOLED - PERIOD 8.86 SEC
- ▽ D - CONDUCTION COOLED - PERIOD 6.998 SEC

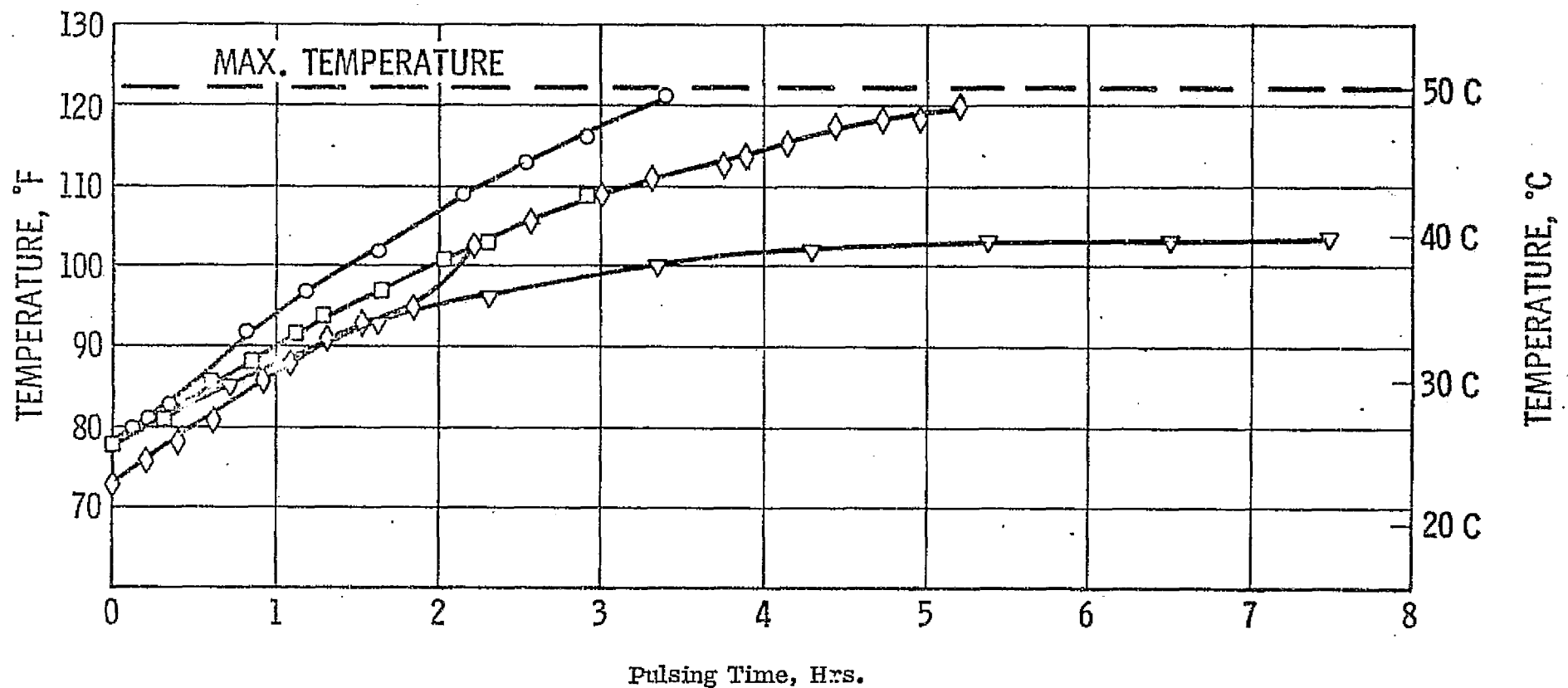


Figure 9. Capacitor Temperature History During Pulse Life Testing in a Vacuum

3.0 CONCLUSIONS

A high voltage 40 joule/lb (88.2 joules/Kg) vacuum compatible energy storage capacitor can be built utilizing vacuum brazing and heli-arc welding techniques. Quality assurance must be maintained at every step of fabrication and both vacuum and high pressure helium leak tests are imperative. Besides removing capacitor self-heat, adequate provisions must be made to intercept and remove heat generated by the discharge load before it becomes transferred to the capacitor.

The double vacuum melt stainless steel was the only item which could be difficult to obtain in future efforts. It would be highly desirable to have a guaranteed source of this material.

A slight decrease in capacitance and increase in dissipation factor appears to be a feature of the particular dielectric system developed when it is subjected to a steady D. C. load over a long time.

Even though the KF-film capacitor has a higher dissipation factor (at 1 KHz) than a Mylar capacitor, propulsive performance is not affected.

More studies should be carried out with this highly promising approach for generating highly reliable space qualified high energy density capacitors.

4.0 RECOMMENDATIONS

While the effort was extremely successful several suggestions can be made with regard to future efforts.

Since the only leaks uncovered occurred with the soldered core of the high voltage stud, it is suggested that a helium leak test be performed after the core is soldered in place but before the redundant sealing cap is installed. Another leak test should be performed after the redundant cap is soldered in place. This two step process may require the use of two solders melting at different temperatures. This area is the only weak area uncovered and perhaps even a different sealing approach might be incorporated in future efforts.

The ground ring design should be modified in future designs to include a flange which can be used to mechanically support the capacitor and facilitate conduction heat transfer to a heat sink.

All capacitors should be subjected to a pulse screening test to weed out infant mortality type failures. This screening test should be carried out under identical discharge conditions which the capacitor eventually will be used. Because of insufficient data at this time it is not known how many discharges have to be performed before the capacitor can be accepted as a "screened" unit.

It is imperative that capacitor life data be obtained under more widely varying conditions in order to establish the voltage-power law of these capacitors.

The decrease in capacitance and increase in dissipation factor that has been observed should be re-examined and explained.

Potential users of capacitors developed under this effort must pay particular attention to the thermal control system to assure that the capacitors will not operate near its upper allowable limit. Perhaps capacitors should be built with either a thermocouple or an RTD inside the capacitor to provide more information of the temperature gradients in this dielectric system.

The specification for the helium leak test should be modified to include a statement of the time duration for the leak test.

Perhaps the fill plug should be modified to a class 3B type fit so that the thread can be more readily pre-soldered before installation.

Since the effort depended upon the availability of double vacuum melt stainless steel, a guaranteed source of this material should be assured.

5.0 REFERENCES

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3. Capacitors for Aircraft High Power, Technical Report AFAPL-TR-74-79, July 1974, Air Force Aeropropulsion Laboratory, Dayton, Ohio, TRW Systems and Energy, Redondo Beach, California.
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FAIRCHILD
REPUBLIC COMPANY

APPENDIX 1

MS005S2300

8 May 1974

Rev. A - 10/25/74

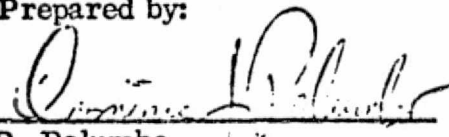
Rev. B - 11/8/74

SPECIFICATION
FOR HIGH ENERGY DENSITY
PULSED DISCHARGE CAPACITOR
FOR SPACE FLIGHT APPLICATIONS

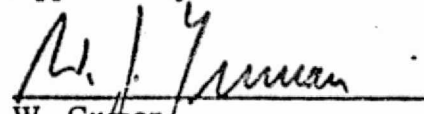
FAIRCHILD

Fairchild Republic Company Farmingdale, L.I. New York 11735

Prepared by:


D. Palumbo

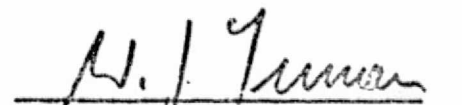
Approved by:


W. Guman

Rev. B Prepared by:


W. Guman

Approved by:


W. Guman, Program Manager

1.0 SCOPE

This specification establishes the electrical and construction design parameters, portions of the manufacturing procedure, and the test requirements for a 60 microfarad high energy density (40 joules / lb) pulsed discharge capacitor to be used on pulsed plasma space propulsion systems. The capacitor will be fabricated and constructed using the best quality control standards available to the manufacturer to insure that all requirements set forth herein are met or exceeded.

2.0 APPLICABLE DOCUMENTS

NASA NHB 5300.4 (1c) "Inspection System Provisions for Aeronautical and Space System Materials, Parts, Components and Services", will be used as a guide by the manufacturer throughout the construction of the capacitor. Procedures called out in this publication should be followed wherever possible although only the documentation specified in this product specification need be supplied.

3.0 REQUIREMENTS

3.1 ELECTRICAL REQUIREMENTS

3.1.1 Capacitance

The capacitance when measured at $+25 \pm 5^{\circ}\text{C}$ and $120 \pm 5\text{ Hz}$ shall be sixty (60) $\pm 10\%$, -5% microfarads as a goal.

3.1.2 Voltage and Energy

The capacitor will be charged to 2500 volts $\pm 1\%$ before each discharge. The capacitor will therefore store 187.5 joules of energy at specified conditions.

3.1.3 Pulse Life

The capacitor design recommended in paragraph 3.3 Dielectric System is presumed capable of producing a capacitor pulse life of one million to ten million pulses under the conditions set forth in paragraph 3.1.2 and 3.1.4 and 3.1.6.

The manufacturer need not verify this pulse life by test, but it is desirable that the actual performance level of the capacitor be established by pulse life tests under conditions permitting extrapolation to those specified.

4 Pulse rate

The most probable pulse rate will be one pulse every six (6) seconds. The maximum pulse rate which the capacitor may possibly be subjected to will be one (1) pulse per second.

3.1.5 Dissipation Factor

The dissipation factor shall not exceed 0.013 when measured at + 25°C and 120 Hz. A design goal of 0.010 or less is preferred.

3.1.6 Discharge load conditions

The design of the capacitor shall be carried out such that it can accommodate the following discharge load conditions and still meet the pulse life expectancy of paragraph 3.1.3.:

3.1.6.1 Peak Discharge Current

The peak instantaneous discharge current is expected to be 25,000 amperes.

3.1.6.2 Initial Rate of Current Increase

The initial rate of current rise into the load is expected to be 10^{10} amperes/sec.

3.1.6.3 Voltage Reversal

The voltage reversal is expected to be 25%.

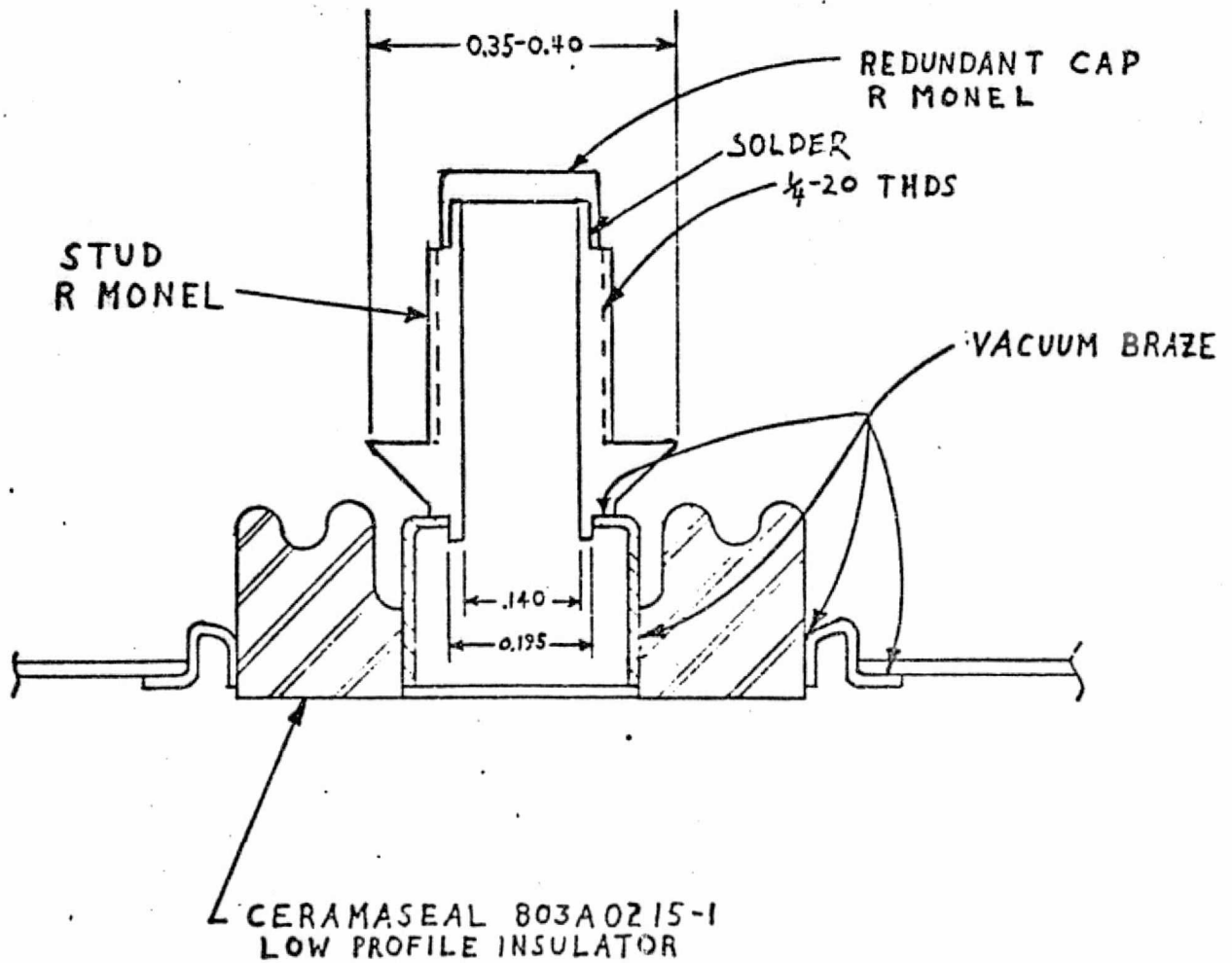
3.1.7 Inductance

The capacitor shall have a maximum self-inductance of fifteen (15) nanohenries

3.2 MECHANICAL REQUIREMENTS

3.2.1 Geometric

The capacitor case with pre-assembled low profile insulator and stud terminal, as well as the ground ring to be furnished by Fairchild Republic Company will be cylindrical in shape with an outside diameter of 4.125 inches and a maximum available length of 7.25 inches (excluding the stud terminals).



NOTES

1. VACUUM BRAZE BY CERAMASEAL
2. LEAKAGE NOT TO EXCEED 1×10^{-9} CC/SEC HELIUM

Figure 1. Hi voltage stud detail to be furnished by Fairchild Republic.
(see Para. 3.2.2)

The length of 7.25 inches can be reduced by the vendor in the event that the requirements of this specification can be met with a shorter overall length. The terminals shall consist of a positive stud centered on one end of the cylindrical case and a ground ring secured to the case on the same end and concentric with the positive stud. The case will form part of the current return path. The rear lid to be furnished by Fairchild Republic will be of a reentrant type configuration.

3.2.2 High Voltage Terminal Configuration

Fairchild Republic Company will furnish the fabricated capacitor case with a modified Ceramaseal low profile terminal 803 A0215-1 and high voltage stud as a pre-assembled and Helium leak tested (to 1×10^9 cc/sec Helium) unit. Unless Fairchild Republic is notified by the vendor within six (6) weeks after program inception of the vendor's requirement for a different stud design, Fairchild Republic will furnish the stud as shown in Figure 1 of this product specification.

3.2.3 Weight (Energy density)

The energy density of the capacitor at the design voltage of 2500 volts shall be 40 joules/lb as the desired goal. If this goal cannot be met, the vendor shall suggest possible means of meeting this goal.

3.3 CONSTRUCTION REQUIREMENTS

3.3.1 Leak tested Welded Seal

The rear reentrant type lid to be furnished by Fairchild Republic shall be Heli-arc welded in an Argon atmosphere by the vendor and subsequently leak tested to have a leakage less than 1×10^{-8} cc/sec Helium. This leak test shall be performed by evacuating the capacitor assembly through the fill hole. Localized rewelding to meet this leakage requirement shall be considered acceptable. This leak test may be supplemented by an additional leak test comprised of pressurizing the capacitor assembly with Helium to a pressure of about 15 psig. The area to be welded shall be solvent-cleaned (200 proof alcohol or equivalent) prior to welding.

3.3.2 Redundant Stud Seal

A redundant sealing cap to be provided by Fairchild Republic shall be soldered by the vendor over the tip of the high voltage stud.

3.3.3 Dielectric System

The recommended dielectric film for the capacitor is KF-film (Polyvinylidene Fluoride) available from Kreha Corporation, 420 Lexington Avenue, New York. Two layers of this film separated by a layer of paper and impregnated with castor oil form the recommended dielectric system. Other dielectric systems will be considered acceptable if the vendor can demonstrate that he can meet the requirements of this specification with another dielectric system. The capacitive element shall be of the extended foil design and of one continuous winding. Splicing of either the dielectric material or conductor shall not be allowed.

3.3.4 Core

The capacitor winding shall begin on an insulating core.

3.3.5 Insulating End Caps

Polypropylene end caps shall be used to eliminate the possibility of flash-over to the case at both ends. The end cap at the high voltage end of the dielectric system shall extend rearward approximately 3/4 inches over the outside of the winding.

3.4 ENVIRONMENTAL REQUIREMENTS

The capacitor is intended to be used over the temperature range +50°C to -35°C in a vacuum of 10^{-4} mm Hg and below.

3.5 FABRICATION REQUIREMENTS

3.5.1 Clean Area

All fabrication and assembly operations of the capacitive element shall be performed in the cleanest (white room) area available in the vendor's plant.

3.5.2 Material Storage

All material and capacitive assemblies shall be stored in containers and in an area which minimizes the possibility of contamination.

3.5.3 Pre-impregnation processes

The vendor shall process and electrically test capacitor pads in the pre-impregnation state to determine:

- a) The dry empirical factor
- b) The dry pot failure point

3.5.4 Pre-impregnation Weibull distribution

The vendor shall plot the Weibull distribution of the pre-impregnation data points and analyze the data for significant test value.

3.5.5 Post-impregnation processes

The vendor shall impregnate the capacitor pads in the dielectric liquid and test them to determine:

- a) The wet empirical factor
- b) The wet dielectric failure point

3.5.6 Post-impregnation Weibull distribution

The vendor shall plot the Weibull distribution of the post-impregnation data points and analyze the data for significant test value.

3.5.7 Final Capacitor design

The final capacitor design shall be in accordance with the vendor's drawings, manufacturing specifications, material and processing specifications and qualification test specifications. These items shall be at a level which will allow the vendor to fabricate identical units at a later date under separate procurement.

3.5.8 Impregnation and Sealing

The capacitors are to be impregnated using whatever method the manufacturer considers necessary to insure complete impregnation of the winding. With the fill hole submerged, cool the capacitor to -20°C and insert the fill hole plug under the impregnant. Solder the fill hole plug with solder that meets specification QQ-S-571.

3.6 TESTING REQUIREMENTS

3.6.1 In-Process Tests

- a) Mechanical: Leak tests of the welded seal shall be in accordance with the requirements of paragraph 3.3.1.
- b) Electrical: The vendor shall perform the electrical in-process tests in accordance with paragraphs 3.5.3 and 3.5.5, respectively. The vendor is also expected to perform any other quality assurances which he believes are necessary to remove population mavericks (parts not characteristic of the population).

3.6.2 Final Screening

A written account of the following screening procedures shall be supplied to Fairchild Republic by filling out the Final Screening Report in the Format of Table 1. for each capacitor. This report, when completed, will be stapled to the historical record in the Format of Table 2. corresponding to the winding in each unit and delivered to FRC with the final screened capacitors.

- a) Weight
- b) Measured capacitance and D.F.
- c) Measured leakage current
- d) The final Hi-Pot voltage to which each unit is to be subjected will be determined by the manufacturer. Apply this voltage and discharge the capacitor through a resistive load which will limit the peak current to 25,000 amperes.
- e) Decrease the Hi-Pot voltage by 1 KV and charge and discharge the capacitor ten times through the same resistance.
- f) Measured capacitance and D.F.
- g) Measured inductance
- h) Leak test
 - 1) Heat the capacitors and maintain 50°C for two hours. Look for signs of oil leakage and deformation of the can.
 - 2) Those capacitors passing the first leak test will then be heated to 40°C for one half hour at 100 microns pressure. Inspect for leaks.
 - 3) Leaky capacitors will not be repaired without FRC approval.

1) Manufacturer screening procedures:

Besides performing the required screening procedures of this specification, the manufacturer may also elect to perform any other screening tests which he believes are necessary to verify the suitability of the capacitor as a high reliability capacitor for space flight applications.

4.0 QUALITY ASSURANCE

All procedures and drawings will be completed under the vendor's Quality Assurance surveillance, and materials and sub-assemblies will be processed through Quality Assurance inspection.

5.0 FAIRCHILD REPUBLIC'S AND CUSTOMER'S (JPL) RIGHTS OF INSPECTION AND TEST

Fairchild and the Jet Propulsion Laboratory of the California Institute of Technology reserve the right to witness any or all of the inspections and tests specified in this specification. Fairchild Republic is to be notified at least ten (10) working days before the manufacturer performs the Final Screening Tests of Paragraph 3.6.2 of this specification.

6.0 DELIVERABLE DOCUMENTATION

6.1 Monthly Communication

A monthly informal communication shall be made between the vendor and Fairchild Republic for the duration of the effort. This communication shall briefly describe the work performed during the month, identifying problems encountered and possible solutions. This communication shall be made not later than the fifth day of the month, following the month being reported upon.

6.2 Test Data

6.2.1 Pre-impregnation Weibull distribution

The vendor shall deliver to Fairchild Republic a reproducible copy of the pre-impregnation Weibull distributor per Paragraph 3.5.4.

6.2.2 Post-impregnation Weibull distribution

The vendor shall deliver to Fairchild Republic a reproducible copy of the post-impregnation Weibull distribution per Paragraph 3.5.6.

6.2.3 Final Screening Report

The vendor shall deliver to Fairchild Republic a reproducible copy of the Final Screening Report in the format of Table 1. of this product specification, (see Paragraph 3.6.2) for each serialized capacitor delivered in accordance with this product specification.

6.2.4 Historical Records of Capacitor Winding

The vendor shall deliver to Fairchild Republic a reproducible copy of the "Historical Record of Capacitor Winding" in the format of Table 2. of this production specification (see Paragraph 3.6.2) for each serialized capacitor delivered in accordance with this product specification.

7.0 SHIPPING

Each capacitor shall be packed by the vendor such that it can withstand transit to Fairchild Republic without incurring damage or deterioration.

TABLE 1.
FINAL SCREENING REPORT

Capacitor Serial Number _____ Date: _____
Winding Number _____
Weight (pounds) _____
Capacitance (microfarads) _____
Dissipation factor _____
Leakage current _____
Hi-Pot test performed at _____ KVDC for _____ minutes.
Capacitor discharged once from _____ KVDC into _____ ohm resistance.
Capacitor discharged ten times from _____ KVDC into _____ ohm resistance.
Capacitance after discharge testing _____
Dissipation factor after discharge testing _____
Inductance _____
Leak test performed by heating capacitor to 50°C for 2 hours.
Result:

Leak test performed by heating capacitor to 45°C for one half hour at 100 microns pressure.
Result:

It is hereby certified that the above tests were performed and the results obtained correct to the best of our knowledge.

Signature: _____

Title: _____

TABLE 2.
HISTORICAL RECORD OF CAPACITOR WINDING

Winding Number: _____ Date Wound: _____

Dimensions of Winding Materials:

Dielectric: Trade Name _____
Width (inches) _____ Thickness (inches) _____

Paper: Trade Name _____
Width (inches) _____ Thickness (inches) _____

Aluminum Foil: Trade Name _____
Width (inches) _____ Thickness (inches) _____

Characteristics of Winding:

Overall Diameter (inches) _____

Capacitance (microfarads) _____

Weight (pounds) _____

Footage (feet) _____

Dry Pot Test performed at _____ KVDC for _____ min.

Capacitance after installation in can (microfarads) _____

Dissipation factor after installation in can _____

Capacitance after welding the can lid (microfarads) _____

Dissipation factor after welding the can lid _____

Passed Helium leak test at 10^{-8} cc/sec. without rework _____

" " " " " " after rework _____

Serial Number of Can/Winding _____

Describe rework required (if any) to pass Helium leak test:

APPENDIX 2

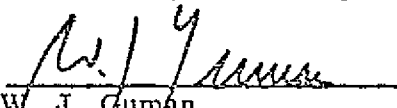
MS005S2301
2 February 1975

PRODUCT SPECIFICATION
FOR
CAPACITOR CAN ASSEMBLY
MS175D1060

FAIRCHILD

Fairchild Republic Company Farmingdale, L.I. New York 11735

Prepared by:


W. J. Guman

Approved by:


W. J. Guman

1.0 GENERAL

It shall be the manufacturer's responsibility to employ sufficient controls, examinations, measurements and tests to ensure that each capacitor can assembly MS175D1060 is free from defects, within required tolerances and is suitable for use in high reliability and long life space flight applications.

2.0 APPLICABLE DOCUMENTS

NASA

NHB5300.4 (1C)

- Inspection System Provision for Aeronautical and Space System Materials, Parts, Components and Services

Fairchild Republic Drawings

MS175D1000

Can, Capacitor Assembly

MS175D1040

Stud

MS175D1050

Ground Ring-Support

MS175D1060

Checker Assembly

MS175D1090

Capacitor Assembly

3.0 QUALITY CONTROL

3.1 Quality Assurance

The vendor shall maintain a quality control system in accordance with NHB 5300.4 (1C).

3.2 Material Control

All material to be used by the vendor shall be procured in accordance with vendor specifications. Traceability of all procured items to appropriate specifications shall be possible.

3.3 Process Control

Manufacturing processes shall be controlled by the vendor's in-house written procedures and instructions and shall be of proven suitability for high reliability aerospace equipment. A copy of the manufacturing and inspection flow chart shall be submitted to Fairchild Republic as soon as possible after program inception.

3.4 Vendor Responsibility

The vendor is responsible for performing all required inspections and tests on a 100% basis and for preparing and maintaining appropriate inspection records.

3.5 ~~Personnel~~ Skills

The vendor shall select persons possessing the highest demonstrated skills to fabricate and test the contract item. All persons working on the contract shall be informed of the fact that the hardware could be used in a satellite. All persons working on this contract must, therefore, be instructed to handle materials and parts with deliberate care to enhance reliability and safety.

3.6 Fairchild Republic's and Customer's Rights of Inspection and Test

Fairchild Republic and the Jet Propulsion Laboratory of the California Institute of Technology reserve the right to witness any or all of the inspections and tests specified in the vendor's manufacturing and inspection flow chart. An inspection plan shall be submitted to Fairchild Republic as soon as possible after program inception. Fairchild Republic shall be notified at least 7 working days prior to the Helium leak test required per Paragraph 4.1 of this specification.

3.7 Incoming Inspection and Material Records

All parts and material to be used shall be subjected to 100% inspection and screening by the vendor. Material certification records shall be maintained.

3.8 Material and Parts Control

The vendor shall implement a system of controls to store all qualified material, components, and parts in a suitable closed area. When not being fabricated or tested, all materials, components, parts and partially-completed assemblies shall be stored therein.

3.9 Spot Welding

Unless specifically agreed upon with Fairchild Republic the MS175D1050 ground ring support is not to be spot welded to the MS175D1000 capacitor can.

4.0 FINAL SCREENING

4.1 Helium Leak Test

Each capacitor can assembly shall be Helium-leak tested not to exceed 1×10^{-9} atm cc/sec. Any unit which does not meet this requirement shall be suitably marked and not reworked without the consent of Fairchild Republic.

4.2 Mechanical

Each brazed assembly shall be inspected to assure that the required dimensional requirements have been met.

5.0 SHIPPING

Each capacitor can assembly shall be packed such that it can withstand transit to Fairchild Republic without incurring damage or deterioration.

6.0 REJECTS

Any completed unit which fails to meet the requirements of this specification shall have the assembly suitably and permanently marked "REJECT". Such rejects are to be returned to Fairchild Republic separately from the acceptable units.